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Super-cooled Large Droplets consideration in the droplet impingement simulation for aircraft icing

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Abstract

Aircraft ice accretion due to Super-cooled Large Droplets (SLD) has been widely concerned since the Roselawn accident, and the airworthiness authority has issued a new notice of proposed rulemaking aiming to the icing condition of SLD. To extend the current water droplet impingement computation code to cover the range of SLD, some typical SLD splashing models was introduced first, and the methods to integrate an empirical SLD model into current impingement code was discussed, although the code has been validated partially in both 2D and 3D conditions for the normal icing envelope defined in CCAR 25 APPENDIX C. Through the comparison of impingement results with the SLD experiment and LEWICE, it could be found that the empirical SLD model can deal with SLD impingement but still need many improvements.

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Keywords: Aircraft icing, Super-cooled Large Droplets, Droplet imingement

1. Introduction

The flight safety hazard constituted by icing conditions of super-cooled Large Droplets (SLD) has been concern by the airworthiness authority since the crash of the ATR-72 commuter aircraft in 1994 at Roselawn [1]. The Federal Aviation Administration [2] has proposed new aircraft icing airworthiness standards at 2010 to improve flight safety by addressing super-cooled large drop icing conditions for transport category airplanes most affected and all the turbine engines.

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Nomenclature

D	Droplet diameter (μm)
V	Droplet velocity (*m/s*)
M_{loss}	Mass ratio splashed
K	Splashing parameter
K_t	LEWICE splashing parameter
La	Laplace number
Oh	Ohnesorge number

So the researches of aircraft icing due to super-cooled large drop become blooming and bring huge challenge to the aircraft icing research. The development of an analytical capability including SLD icing conditions was considered a major technical area inside the draft SLD Engineering Tools Development Project Plan developed by the Ice Protection Harmonization Working Group (IPHWG) at 2003 [3].

The water droplet impingement analysis is the key step to ice accretion simulation, including the analysis of areas and components to be protected, the impingement limit, and the local collection efficiency. SAE ARP5903 [4] summarized information, guidelines, and practices for the application, use, and administration of two-dimensional and three-dimensional droplet impingement and ice accretion computer codes for the purpose of the certification. But most of them focused on the droplet diameters defined in FAR 25 Appendix C.

To enhance the ability of LEWICE for SLD condition, Wright [5] systemically reviewed the current assumptions in the droplet trajectory equations of LEWICE, involving solid and spherical particles with out breaking up or rotation, negligible evaporation, lift or moment of the drops, neglected turbulence effects, and so on. Finally he found that splashing is the first order important factor for SLD simulation.

However, the numerical model of droplet splashing would require solving the Naviér-Stokes equations for each droplet impact using a Volume of Fluid (VOF) or level set model, which computational burden is too heavy to be applied in the droplet impingement code for aircraft icing typically involving thousands of droplet impacts per second. Currently the detailed numerical computation is limited in the field of the interaction between a single droplet and wall, dry or wet. Combined with the experiments, the researcher brought out many droplet splashing models [6], such as Lee and Ryou Model, Stanton and Rutland Model, Marengo and Tropea Model, Schmehl Model, Trujillo Model, and Samenfink Model.

Wright [6] adapted the Trujillo Model based on the SLD experiment data and then incorporated a semi-empirical computational model of droplet splashing into the LEWICE and GLENNICE [7] software. Although the ranges of applicability of such splashing model are limited due to lower drop size, velocity and droplet impinge frequencies comparing with real flight condition, such correlations are still improved the simulation accuracy for the range of SLD ice accretion because of the adjustments based on experiments of SLD impingement. So this model has been adopted by most of the aircraft icing simulation code currently.

Beside that, Tan [8] found that amount of mass loss from splashing depends on the droplet median volume diameter , impact parameter and a splash constant, and then proposed an interesting droplet splashing model, with the form as ψ = C1+C2*(C3) , where, C1= splash constant , C2 = f (MVD) , C3 = f (impact parameter, K). While Tan did not publish the value for C1, C2 and C3 because of limited tests at the preliminary stages of research. Further more, the splash parameter also does not consider the effects of film thickness, roughness or splash re-impingement.

The objective of this paper is to extend the water droplet impingement simulation code to the range of super-cooled large droplet, while the code has been validated partially in both 2D and 3D conditions for the icing envelope defined in CCAR 25 APPENDIX C. Some typical SLD splashing models will be briefly introduced first, and the methods to integrate an empirical SLD model into current impingement code will then be discussed.

2. Some typical SLD splashing models

Generally speaking, to empirically model the phenomena of the large drop splashing, the basic parameters needed includes the splashing threshold, the splashed drop size (or drop size distribution), the splashed velocity (or a distribution of splash velocities), the splash angle (or a distribution of splash angles) and the amount of splashed mass.

2.1. Samenfink Model

Samenfink model [9] maybe the best one to understand the process of the droplet impacting on the wet wall surface, which is similar in aircraft icing process. As indicated in Fig. 1, the typical primary droplets with the velocity c_{iD}, the diameter D_{iD} and the impingement angle α_{iD} impinged on the shear driven liquid film with the mean film height h_F, the mean film velocity c_F and the wave angle α_{wa}. So the impinged angle to the wave surface becomes α_{imn}.

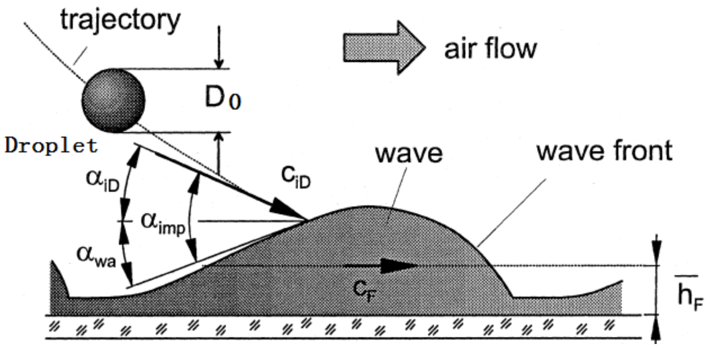


Figure 1 The illustration of drop impact on the wet wall (Revised From reference [9])

Samenfink brought out a simple criterion, the droplet momentum *S*, to determine whether the splash happens or not. If the droplets impacting the film with a high momentum, $S > 1$, will be destroyed and secondary droplets will be formed.

So the original format of Samenfink model could be listed as follow,

$$S = \frac{R_e}{24La^{0.419}} \tag{1}$$

Diameter distribution,

$$\frac{D_s}{D_0} = 1 - 0.03454S^{0.175}\alpha_{iD}^{0.1239}La^{0.265} \tag{2}$$

Velocity ratio,

$$\frac{V_s}{V_0} = 0.08214 S^{-0.03384} \alpha_{iD}^{0.2938} \delta^{-0.03113} La^{0.01157} \quad (3)$$

Secondary droplet splashing angle,

$$\theta_s = 2.154 S^{1.0946} \alpha_{iD}^{0.03389} \delta^{-0.1589} \quad (4)$$

Secondary droplet velocity,

$$V_{n,s} = V_s \sin\left(\frac{\pi\theta_s}{180}\right) \quad (5)$$

$$V_{t,s} = V_s \cos\left(\frac{\pi\theta_s}{180}\right) \quad (6)$$

Mass ratio,

$$\frac{m_s}{m_0} = 0.0866\left(S-1\right)^{0.3188} \alpha_{iD}^{0.1223} \delta^{-0.9585} \quad (7)$$

where dimensionless Laplace number $La = \frac{\rho_d \sigma D_0}{\mu^2} = \frac{1}{Oh^2}$, Ohnesorge number, $Oh = \mu_d / \sqrt{\rho_d \sigma D_0}$, μ_d is the droplet viscosity (kg/m/s), ρ_d is the water drop density (kg/m^3), σ is the surface tension between air and water (kg/s^2). The dimensionless film thick could be calculated as $\delta = \overline{h_F} / D_0$ or by Eq. (8) when applied in the field of aircraft icing:

$$\delta = 3.76\left(\frac{D_{le}}{D_0}\right)^{1.25} \left(\frac{LWC}{\rho_w}\right)^{0.5} We_{le}^{-0.125} \quad (8)$$

Where the D_{le} is the diameter of the leading edge of the airfoil. The applicable range of above equations is: $1.0 < S < 5.0$, $5000 < \text{La} < 20000$, $0.3 < \delta < 3.0$ and $5° < \alpha_{iD} < 90°$.

2.2. Schmehl Model

Schmehl model [10] is similar to the previous one and adopted the same splashing criteria, but is much simplified to be used. They assumed that the splash velocity was 60% of the incoming velocity and selected the following expressions for the remaining terms:

Secondary droplet velocity,

$$V_s = 0.6 V_0 \quad (9)$$

Secondary droplet diameter distribution,

$$\ln\frac{D_s}{D_0} = -2.0 - D_0 / 4066 - 0.05S \quad (10)$$

Splashed mass ratio for dry wall,

$$\left(M_{loss}\right)_{dry} = 1 - S^{-0.6} \quad (11)$$

Splashed mass ratio for wet wall,

$$\left(M_{loss}\right)_{film} = \left(M_{loss}\right)_{dry} e^{-\delta} \quad (12)$$

2.3. GlennICE model

As discussed in Introduction, the GlennICE model [7] comes from Tr. The dimensionless mass fraction of water lost due to bouncing or splashing M_{loss} could be calculated by,

$$M_{loss} = \begin{cases} 0 & K_t \le 200 \\ 0.7\left(1-\sin\alpha_{imp}\right)\left(1-e^{-9.2(K_t-200)/1000}\right) & K_t > 200 \end{cases} \tag{13}$$

Where, α_i is droplet impact angle (degrees), and inertia parameter,

$$K_t = 0.859\left(\frac{\rho_l}{LWC}\right)^{1/8}\sqrt{Oh\times \mathrm{Re}_d^{1.25}}\;/\left(\sin\alpha_i\right)^{5/4} \tag{14}$$

The other parameters of the secondary droplet could be determined as follows,

$$\frac{D_s}{D_0} = 8.72e^{-0.0281K} \tag{15}$$

Where the splashing number $K=\mathrm{Oh}_w\,\mathrm{Re}_w^{1.25}$.

$$V_{s,x} = V_x\left(1.075-0.0025\alpha_{imp}\right) \tag{16}$$

$$V_{s,y} = V_y\left(0.3-0.002\alpha_{imp}\right) \tag{17}$$

3. NUMERICAL SIMULATION OF THE WATER IMPINGEMENT CONSIDERING SLD

3.1. The general framework

The general framework of water droplet impingement analysis in Lagrangian approach is well-known, where the flow field around will be generated firstly and then the water droplets will be released and tracked until they impinge on the body, which could be summarized as following steps,

Step 1: Generate a flow field around the body to be analyzed using panel method or computational fluid method by solving Reynolds Average Navier-Stokes (RANS) equations with an Eulerian mesh. Although the larger drop may have greater effects on the air flow, the computation of the air flow can be decoupled from the calculations of water drop motion due to the little fraction of water drops.

Step 2: Release droplets from somewhere upstream, where are far enough from the body surface and the droplets released here will impact on surface finally.

Step 3: Track each droplet during its movement by calculating the force acting on it, which need to locate the hosting elements and interpolates the fluid property at each droplet position in the Eulerian mesh.

Step 4: Integrate the trajectory until it intersects with the body surface or runs out of the computational domain.

Step 5: Analyze the impingement efficiency by tracking enough droplets and considering the droplet-splashing if need.

The implementation of above process and detailed mathematical model could be found in Reference 11 ~ 12.

3.2. Computation of the impingement efficiency considering the splashing

As demonstrated in Fig. 3(a), the droplets released from region *S* will impinge at region *R*, where the impinged boundary is represented by Γ_b. The impinged boundary is known as the impinged limitations for 3D condition.

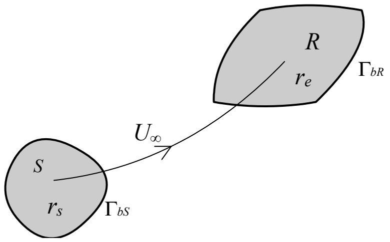


Figure 2 The scheme of the determination of the impingement limitations

The local impingement efficiency values can be directly calculated from the ratio of the area delimited by some trajectories (usually four trajectories is enough) away from the body to the corresponding impinged region formed by the impact trajectories intersect the face, as given by Equation (18),

$$\beta = A_p / A_u \tag{18}$$

Where, A_p is the area of the element on the body surface, the A_u is the stream tube area at somewhere upstream, which is formed by the position from where droplets released will impact at the panel/element corner. Droplet cannot be reversed track in the flow field, so such positions had to be determined by iterative computation, which is time-consuming.

While considering the effects of the phase change and splashing, the new computation could be defined through a simple arithmetic average as follow,

$$\beta = \frac{A_p}{4A_u}\sum_{i=1}^{4}\left(M_{unsplashed} \times \frac{r_e^3}{r_s^3}\right) \tag{19}$$

Where the r_s and r_e are the radius of the droplet released and impinged in case of the consideration of the phase change.

The impingement efficiency for general body shape was achieved with the aid of the cover ratio of impact, and then the whole process could be summarized as following steps,

Step 1: Determine the impingement limitations and corresponding droplet released region.

Step 2: Release $N \times N$ droplets from the released region upstream, track them and find the impinged positions.

Step 3: Calculate the impingement efficiency for each impinged region constructed from the adjacent impinged positions with the aid of Equation (19).

Step 4: For each impinged region, find all the surface elements fully or partially covered by this region with the four impinged points and the grid topology information, and then calculate the cover ratio for each element.

Step 5: Compute the impingement efficiency for each surface element according to the methods introduced in Reference 11.

More details about the above process could be found at Reference 12.

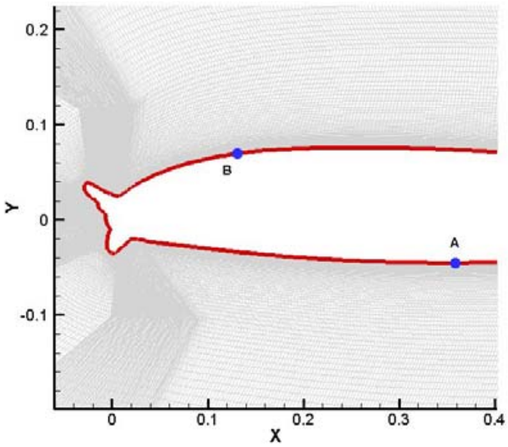
4. Validations with the integration of SLD model

NASA Glenn Icing Research Tunnel (IRT) [13] conducted a series of water droplet impingement experiments for a 36-in chord NACA23012 airfoil with five simulated glaze ice shapes, which were generated using LEWICE. During these tests, the air speed is 175 mph, the angle of attack of model is 2.5 degree, and the results were compared with analysis impingement data computed from the LEWICE code. Four simulated ice shapes of 5-min, 10-min, 15-min and 22.5-min were used here and represented by E1, E2, E3 and E4, as defined in Reference 11.

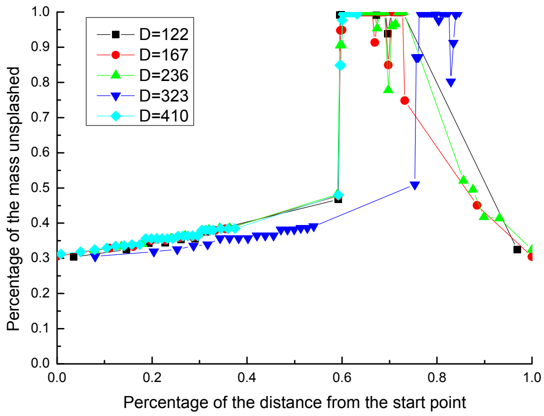
Here we adopted the flow field simulation results from Reference 11, which agree very well with the experimental data for all the four complex ice shapes. The results also showed the advantages of the grid based Navier-Stokes solver over the panel method in simulating viscous flow fields with extensive flow separation. However, the splashing model used in Reference 11 is coming from the user manual of LEWICE 3.2 [14], which is a little different from here. In this paper, we choose the SLD model used in GlennICE software [7] due to that it is has been validated by many real experiment cases of SLD impingement.

Figure 3 gave the computational grid and the un-splashed mass ratio distribution along the iced airfoil from the lower side impingement limitation (point A) to the upper side impingement limitation (point B) for five different droplet diameters: 122 μm, 167 μm, 236 μm, 323 μm and 410 μm.

As shown from Figure 3(b), nearly 60% ~ 70% drops splashed near the position of the impingement limitation due to the bigger impinge angle. It indicated that the impinge angle is the most important factor in current SLD splashing model.



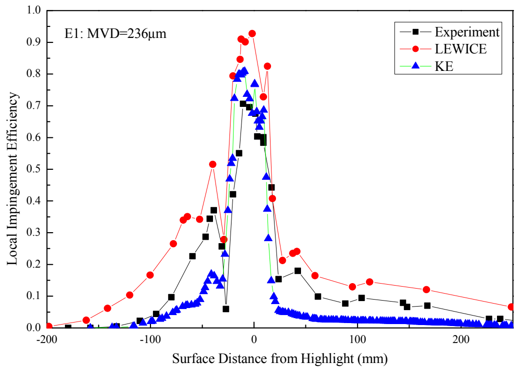
(a) the grid and impingement limit



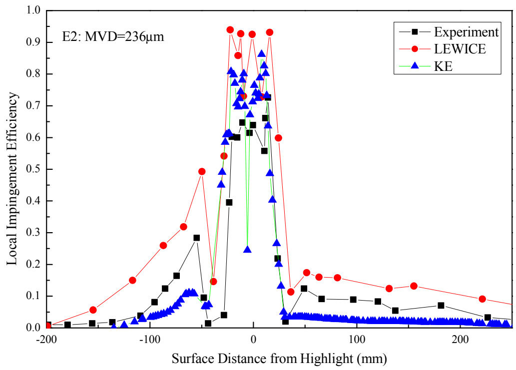
(b) the mass percent un-splashed along ice shape for E4

Figure 3 The distribution of un-splashed mass ratio along the 2D iced airfoil for E4

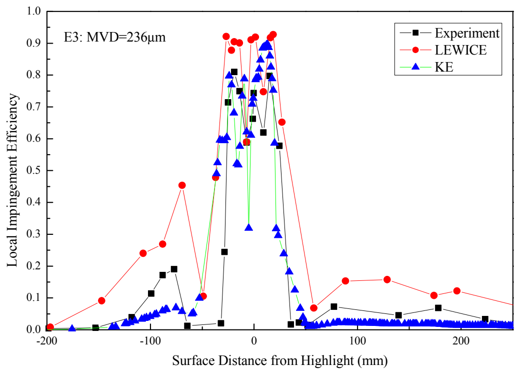
It was further proved by the local impingement efficiency distribution of all the four iced airfoils, as shown in Figure 4, where the comparison is conducted with the results of experiments and LEWICE code from Reference 13. The droplet impingement computations were conducted for the super-cooled large droplet with the MVD of 236.0 μm with Langmiur-D droplet size distribution. It can be found that the local impingement efficiency from our numerical simulation (indicated as KE) is agreed with the experiments (indicated as Experiment) better than those from LEWICE (indicated as LEWICE). However, it is over estimated the local impingement efficiency near the stagnation point, while is under estimated near the points of the impingement limitations.



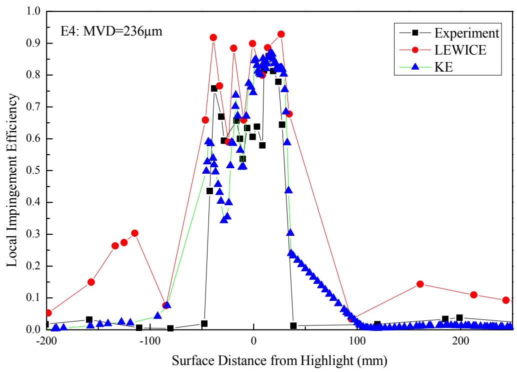
(a) MVD is 236.0 μm for E1



(b) MVD is 236.0 μm for E2



(c) MVD is 236.0 μm for E3



(d) MVD is 236.0 μm for E4

Figure 4 Comparisons of the local impingement efficiency of 2D iced airfoil (Langmiur-D)

5. Conclusions

Because of the complexity of physics of large droplet dynamics during impact, such as bounce, distortion, splashing and so on, it is hard to model such phenomena experimentally or numerically. So the SLD impingement problem has not been well solved, although the computation of droplet impingement using Lagrangian method has developed for many years.

From our research, it can be concluded that the current empirical SLD model could be integrated into the current droplet impingement code, and account for some splashing effect along the impinged zone. However the impinged angel has too many effects on this model, so it deviated much more from the experiment in water impingement near the stagnation point than near the impingement limit.

More fundamental researches should be carried out focusing the physics of larger drop impacting and splashing to improve the SDL model adopted in aircraft icing simulation.

Acknowledgements

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